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HEAT FLOW vs. ATMOSPHERIC GREENHOUSE on EARLY MARS

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Long term climate change on Mars is suggested by an apparent difference in the erosional style exhibited by the ancient cratered terrain as opposed to terrain of later origin. In particular, the morphology and distribution of valley networks on Mars clearly indicates a difference in erosional style ~3.8 billion years ago versus mid-to-late martian history. Liquid water was certainly involved in network formation, although sapping processes rather than rainfall seem indicated. Two major factors could have contributed toward making early conditions more favorable to formation of valley networks:

First, it has been argued (1) that higher internal regolith temperatures, associated with a much higher heat flow 3.8 AE, would cause groundwater to be closer to the surface then than at present. Higher heat flows are expected early in Mars' history primarily because of dissipation of the original heat of formation, although a higher rate of production of radiogenic heat is also a factor.

Second, if enough CO_2 is in the atmosphere, surface temperatures could be raised, due to an increased atmospheric greenhouse effect, to near the freezing point of water despite a weak early sun - at least at the equator and for the most favorable part of the orbital and axial cycle. Current greenhouse models indicate that CO_2 surface pressures of between about 0.75 and 5 bars are needed to raise the surface temperature on early Mars to the freezing point of water. Only slightly lower pressures characterize greenhouse warmings that are 10 to 20° K cooler.

In fact, the effectiveness of both these mechanisms is dependent on a high early heat flow: In the case of the atmospheric greenhouse, this is because the atmospheric mean residence time (M.R.T.) of CO_2 in the presence of fluvial activity is believed to be much shorter than the span of time over which network formation occurred. Thus, the atmospheric P_{CO_2} would have been dependent almost exclusively on the recycling time for regolith carbonate rather than the instantaneous supply of juvenile CO_2. Both of these parameters can be quantitatively related to the heat flow. The depth to the water table, ΔZ_{273}, also depends on internal regolith temperatures. For a given regolith conductivity, k, the temperature at any depth is determined by the heat flow, which determines the gradient, $\partial T/\partial Z$, and the surface temperature, T_S.

We have derived a quantitative relationship between the effectiveness of an atmospheric greenhouse and internal heat flow in producing the morphological differences between early and later martian terrains. Our derivation is based on relationships previously derived by other researchers (2). Thus, while the validity of our derivation is dependent on the validity of these previously derived relationships, no new assumptions or mathematical relationships are necessary - merely algebraic manipulation of relationships already in the literature.

Our reasoning may be stated as follows: The CO_2 mean residence time in the martian atmosphere, although not well known, is almost certainly much shorter than the total time span over which early climate differences are thought to have been sustained . Therefore recycling of previously degassed CO_2 quickly becomes more important than ongoing supply of juvenile CO_2 . If so, then the atmospheric CO_2 pressure - and therefore the surface temperature - may be approximated mathematically as a function of the total degassed CO_2 in the atmosphere plus buried material and the ratio of the atmospheric and regolith mean residence times. The latter ratio can also be quantitatively expressed as a function of heat flow . Hence, it follows that the surface temperature may be expressed (given assumptions as to regolith conductivity) as a function of heat flow and the total amount of "available" CO_2. However, the depth to the water table - again assuming the same regolith conductivity - can simultaneously be expressed as a function of heat flow and the surface temperature (the boundary condition). Therefore, for any given values of total available CO_2 and regolith conductivity, there exist coupled independent equations which relate heat flow, surface temperature and the depth to the water table. This means that we can now derive <u>simultaneous</u> values of surface temperature and the depth to the water table for <u>any</u> value of the heat flow. We utilize the derived relationship for two purposes: 1) To evaluate the <u>relative</u> importance of the atmospheric greenhouse effect and the internal regolith thermal gradient in producing morphological changes for <u>any</u> value of the heat flow and 2) to assess the <u>absolute</u> importance of each for values of the heat flow which are thought to be reasonable on independent <u>geophysical</u> grounds.

Figure 1 illustrates that for a given amount of total available CO_2, regolith conductivity and atmospheric M.R.T., the relative roles of internal heat flow and atmospheric greenhouse are inextricably interlocked. Figs. 1a and 1b are for a case of a cool early sun, favorable orbital situation, and an equatorial site (after ref. 2). The mean residence time of atmospheric CO_2, and regolith conductivity are the same in both figures. The figures show surface temperature (T_s) as a function of depth to the water table (z). The numbers in parentheses indicate heat flow in mW m^{-2}.

In Figure 1a, total CO_2 = 3.5 bars. Note that the internal heat flow predicted by (1) for ~3.8 AE ago, that is ~150 mW m^{-2}, is more than sufficient to recycle enough CO_2 to keep surface temperature at the freezing point because we have assumed so much <u>total</u> CO_2. In this case, the surface greenhouse effect plays a dominant role. However, if one considers that a water table depth of < 350 m is sufficient to permit widespread sapping, it is clear that the internal thermal gradient also plays a major role in widening the latitudes and time bands in which sapping would be prevalent. Thus this case is not very different either in assumptions or result from those discussed by (2).

In Figure 1b total CO_2 is only one bar. This case is important because in many plausible versions of the early Mars volatile inventory it is entirely possible that the total available CO_2 at 3.8 AE might have been only a bar, or even less. In this case we find that the atmospheric greenhouse effect plays almost no role because the low total CO_2 abundance requires incredibly fast recycling in order to keep any significant abundance in the atmosphere. Thus for plausible values of earlier heat flow, the surface temperature changes by only a few degrees. On the other hand, the early heat flow produces an enormous direct effect on the depth to the 273K isotherm despite the near constancy of surface temperature; at Q = 30 mW m^{-2} the depth is over a km, but at Q = 100 mW m^{-2} it is less than 300 m and near the critical depth suggested by (1).

All these calculations are sensitive to the values chosen for the (unknown) regolith conductivity, the CO_2 atmospheric mean residence time, and especially total CO_2 inventory assumed. Thus it is important to explore the sensitivity of the conclusions to the values chosen. Although our exploration of the parametric space has been limited, the qualitative characteristics of the system are apparent.

We find that if the total available CO_2 has always been ~4 bars or more, then the atmospheric greenhouse effect can easily account for the change in erosional style, and the primary role of the heat flow is to raise ground water temperatures. This result is in keeping with the earlier results of (2). On the other hand, if the total CO_2 were only ~1 bar, the atmospheric greenhouse effect does not raise the surface temperature by more than a few degrees, but for plausible values of regolith conductivity the change in internal gradient accompanying higher early heat flow can still easily decrease the water table depth by a large factor, from well over a kilometer to less than 350 m, enabling network formation at 3.8 AE.

REFERENCES: (1) Squyres, 1989. Fourth International Conf. on Mars, Tucson, AZ. (2) Pollack et al., 1987. Icarus *71*, 203-224. (3) Schubert et al., 1979. Icarus *38*, 192-211.